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Optimization of passive solar design strategies: A review ☆

Sanja Stevanović [a,b,*]

[a] University of Primorska, Institute Andrej Marušič, Muzejski trg 2, 6000 Koper, Slovenia
[b] University of Niš, Faculty of Sciences and Mathematics, Višegradska 33, 18000 Niš, Serbia

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ABSTRACT

Passive solar design strategies comprise important ways of reducing the heating, cooling and lighting energy consumption of buildings. Although it is relatively simple to reduce the energy use up to some extent by applying individual strategies, very high levels of energy performance require application of the optimal combination of several strategies, verified through building energy simulations. Here we give an exhaustive review of the previous studies of simulation-based optimization of passive solar design strategies, with particular focus on recent research results.

Contents

1. Introduction

The recent recast of the EU Energy Performance of Buildings Directive, requesting all new buildings in the EU to consume "nearly zero" energy after 2020, requires buildings' energy efficiency to be raised to a higher level through the coherent application of passive and active design strategies reducing heating and cooling loads, raising equipment energy efficiency and the use of renewable energies. In order to lessen the burden on the active systems transforming renewable energy into the thermal or electrical energy, a necessary first step is to apply the optimal combination of passive design strategies, foremost among them passive solar design strategies.

Passive solar design strategies aim to use the solar energy to help to establish the thermal comfort in buildings, without the use of electrical or mechanical equipment. The greatest opportunities for the integration of the passive solar design strategies occur at the conceptual design level, by determining the values of parameters that have critical influence on building performance, such as building form, opaque envelope components, glazing and its shading, etc. Building energy simulation plays a fundamental role in this process since the building's future response to applied passive design strategies is highly sensitive to the local climate

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* Corresponding author at: University of Niš, Faculty of Sciences and Mathematics, Višegradska 33, 18000 Niš, Serbia. Tel.: +381 63 1045 159; fax: +381 18 533 014.
E-mail address: sanja_stevanovic@yahoo.com

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Nomenclature

ASHRAE	American Society of Heating, Refrigerating and Air Conditioning Engineers
CFD	computational fluid dynamics
CH4	methane
CO2	carbon dioxide
EN ISO	International Organization for Standardization, European Norm
EU	European Union
HVAC	Heating, Ventilation and Air Conditioning
N2O	nitrous oxide
NOx	nitrogen oxides
PV	photovoltaics
RCCTE	Regulation of Characteristics of Thermal Performance of Buildings (in Portuguese)
SOx	sulphur oxides
U-value	thermal transmittance
UAE	United Arab Emirates
UK	United Kingdom
USA	United States of America

Software

ADELINE	daylight and artificial lighting simulation [114]
BEopt	building energy optimization software [27]
DEROB-LTH	dynamic energy simulation [95]
DOE-2	building energy use and cost analysis [22]
EC501	building thermal performance calculation [71]
ENERGY	building thermal performance prediction model [47]
EnergyPlus	energy simulation software [31]
eQUEST	quick energy simulation tool [105]
ESP-r	integrated energy modelling tool [78]
FLUENT	computational fluid dynamics software [108]
GenOpt	generic optimization program [34]
HTB2	thermal simulation of buildings [69]
IDA ICE	indoor climate and energy tool [82]
IES-VE	building performance simulation [100]
LT method	energy performance curves estimation [120]
modeFRONTIER	multi-objective optimization and design environment [67]
OPTI	energy consumption, thermal comfort and daylighting [124]
PHPP	passive house planning tool [87]
RADIANCE	synthetic imaging system [53]
SIMBAD	building energy consumption tool [39]
SUNCODE-PC	building thermal analysis simulation [93]
TAS	thermal analysis simulation software [107]
THERB	thermal environment simulation software [129]
TRNSYS	transient system simulation tool [25]
VisualDOE	building energy simulation software [142]
ZEBO	decision support tool for zero energy design [30]

factors. However, due to the usually extremely large size of the building design space, it is close to impossible to reach a high level of performance with the trial-and-error approach alone. Thus, it becomes necessary to use an optimization method coupled with the energy simulations in order to choose the optimal combination of passive solar design strategies for a given location.

The manuscript thus provides an exhaustive review of existing studies of simulation-based optimization of passive solar design strategies, whose annual counts are shown in Fig. 1, with particular focus on the recent research results. Section 2 reviews the optimization methods and software used in these studies. Section 3 reviews the optimization studies of a restricted set of passive solar design strategies, focused either on the building form, or opaque envelope components, or glazing and its shading, and Tables 1–3 contain summaries of studies reviewed in its corresponding subsections. Section 4 reviews studies which aim to simultaneously optimize a more comprehensive set of passive solar design strategies, trying to optimize whole building's passive behaviour and response, and Table 4 contains summaries of studies reviewed in this section.

However, as the passive solar design strategies are the subject of extensive research, the rest of this introductory section first presents an overview of the other review papers that cover particular aspects of passive solar design.

Sadineni et al. [1] provide exhaustive technical review of the building envelope components for the potential of their passive energy savings. They review selected types of walls, such as Trombe walls, ventilated walls and glazed walls, fenestration technologies including aerogel, vacuum glazing and spectrally selective low-e coatings, roofing techniques such as green roofs, photovoltaic roofs, radiant-transmissive barrier and evaporating roof cooling systems, as well as the use of thermal insulation and phase-change materials.

Pacheco et al. [2] review the building design criteria that can reduce energy demand for heating and cooling of the residential buildings. These criteria discuss suitable parameters for the building orientation, shape and the ratio of building surface and volume, building envelope and its U-value, glazing and shading, and passive heating and cooling mechanisms.

Charron and Athienitis [3] review existing guidelines for the design of low and net zero energy solar homes with respect to landscaping, floor plan and orientation, thermal mass, windows and sizing HVAC systems, the relevant technologies for meeting the heating loads in heating-dominated climates, the role of the building simulation tools and their coupling with genetic algorithms in the search for optimal designs.

Thermal insulation is one of the most valuable tools in achieving energy conservation in buildings. Kaynakli [4] reviews the methods for determining the optimum thickness of the thermal insulation in a building envelope, in particular, the optimum economic thickness, which is the value providing the minimum total lifecycle cost of insulation. Kaynakli [4] also discusses the effects of thermal insulation on reducing energy consumption, greenhouse gas emissions and environmental impact.

Jelle [5] reviews the advantages and disadvantages of an exhaustive list of thermal insulation materials and solutions, classified as traditional (mineral wool, expanded and extruded polystyrene, polyurethane, cellulose, cork), state-of-the-art (vacuum insulation panels, gas-filled panels, aerogels, phase change materials) and new conceptual thermal building insulation (nano-insulation materials, dynamic insulation materials, nano-concrete). Their various properties, such as thermal conductivity, perforation vulnerability, building site applicability and cuttability, mechanical strength, fire protection, water and freezing resistance, costs and environmental impact have been compared and studied.

Chan et al. [6] review, on one hand, technologies for passive solar heating via buoyancy effect (Trombe wall, solar chimney, unglazed perforated-absorber collector and roof-based systems) and, on the other hand, technologies for passive solar cooling via evaporative effect and their building integration.

Saadatian et al. [7] review nine types of Trombe walls: classic, zigzag, water Trombe walls, solar transwalls, solar hybrid walls, Trombe walls with phase-change materials, composite, fluidised and PV-Trombe walls. Trombe walls may provide thermal comfort and reduce a building's energy consumption, as well as decrease the moisture and humidity of the interior spaces in humid regions.

Table 1
Summary of research on optimization of building form.

Objective function (s)	Design variables	Optimization method	Simulation method	Case study location	Major findings/limitations	Ref.
Heat flow	Envelope triangulation	Genetic alg.	EnergyPlus		Optimal form has slightly concave south, east and west surfaces for proper self-shading in summer	[45]
Cooling load, lighting load	Facade type (vertical or self-shading), glazing type, presence of internal blinds, facade orientation	Parametric study	ENERGY	Israel		[46]
Construction cost, heating load	Southern and northern parametrized semiovals as the building footprint	Variational method		Poland	Optimal solution, consisting of a semicircle in north and a parametrical curve in south, performs better than a circular base	[48]
Solar irradiation on building surface	Height of different building parts	Evolutionary algorithm	RADIANCE		Northern parts are all at maximum height, while the south and west parts are at irregular heights	[52]
Solar irradiation on urban forms in heating season	Facade heights, roof orientation and heights	Evolutionary algorithm	RADIANCE	Switzerland		[54]
Solar irradiation of the equatorial-facing facade	Seven building shapes, shape aspect ratio	Parametric study	EnergyPlus	Canada	Solar potential is maximized by reducing the ratio of shading to shaded facade lengths and increasing the angle enclosed between shading and shaded facades	[55]
Energy demand of housing units on a neighbourhood scale	Building shape, unit orientation, unit densities, site layout	Parametric study	EnergyPlus	Canada	Units in curved layouts have larger heating and cooling loads than in a straight road configuration	[56]
Heating load	Shape coefficient	Parametric study	Response factors method	France	The heating load in cold climate is almost directly proportional to the shape coefficient, but no correlation between the heating load and the shape coefficient is observed for mild and sunny climates	[57]
Heating load	South exposure coefficient	Parametric study	ISO 13790	Italy	The south exposure coefficient, defined as the ratio of the area of the south walls to the building volume, correlates well with the heating load in mild and sunny climates	[58]
Annual energy cost, construction cost	Building relative compactness, walls and roof insulation levels, windows-to-wall ratio, glazing type	Neural networks, genetic alg.	DOE-2	Egypt, USA, Italy, Tunis		[59]
Energy demand, lifecycle cost	Building shape, orientation and aspect ratio, wall, roof and floor insulation levels, windows area, glazing type, infiltration rate, thermal mass	Genetic alg.	DOE-2	USA	The building shape design variables have less impact on building energy use than the other design variables	[60]
Lifecycle cost, lifecycle environmental impact	Polygonal shape of building footprint, structural system, insulation levels, glazing type, windows-to-wall ratio, overhangs presence, depth and height	Genetic alg.	Unknown	Canada	Solutions with lower lifecycle cost have shapes close to the regular polygon, while solutions with lower lifecycle environmental impact have larger edge length on the south facade	[61]

However, they also suffer from the shortcomings such as low thermal resistance, possibility of reverse heat transfer and lack of architectural beauty. Especially in well-insulated buildings, the Trombe walls may function as a source of undesired heat gain, making necessary proper insulation of the interior side of the mass wall.

Shi and Chew [8] review the research on the influence of geometric conditions and design factors on the performance of solar chimney system, including the closed-form expressions describing the average air velocity inside solar chimney as a function of its parameters. Although the optimum inclination angle for maximizing airflow depends on latitude of the location, it has been found that it is usually between 40° and 60°. Same as for Trombe walls, insulation of the interior side of the mass wall is necessary in solar chimney. Shi and Chew [8] also review the energy saving potential of various fenestration options: side windows, clerestories, light shelves, louvers, prismatic glazing, skylights, roof monitors and light pipes.

Thirugnanasambandam et al. [9] review the thermal performance and mathematical models of various devices aimed at using solar energy for heating and cooling in buildings, such as solar chimneys, solar heated thermal storage, cool solar roofs and Trombe walls. They also provide review of other solar thermal technologies, such as solar water heaters, solar cookers, solar driers, solar ponds, solar air-conditioning, solar power plants and solar stills.

Even for suitable regions where solar irradiation is high and wind speed is normally low, a solar chimney alone has limited potential in inducing sufficient natural ventilation to satisfy indoor thermal comfort. Zhai et al. [10] provide a review on integration of solar chimneys with other passive systems, such as Trombe walls, roof solar collectors, earth to air heat exchangers, evaporative or solid adsorption cooling cavities, as well as with the active solar systems, utilized to enhance the ventilation performance of solar chimneys. They also indicate the need for further research on the optimization and control strategy of such integrated systems in different climates.

Green roofs offer many benefits for buildings and their surrounding environment, such as better stormwater management, improved urban air quality and enhanced architectural image. They also help to reduce urban heat island effect through the improved reflectivity of the incident solar radiation. Castleton et al. [11] review the benefits green roofs offer in relation to the building energy consumption. Since the insulation properties of green roofs cannot measure up to the modern roof insulation materials, the green roofs will save very little, if any, energy in new buildings made to meet strict building U-value regulations. However, they can significantly reduce energy use in the existing

Table 2
Summary of research on optimization of opaque envelope components.

Objective function(s)	Design variables	Optimization method	Simulation method	Case study location	Major findings/limitations	Ref.
Bioclimatic margin	Insulation thickness	parametric study	Theoretical model	France	The first few centimeters of insulation in mild climate have the largest influence, while further thickness increases have progressively smaller influence	[62]
Cooling load	Cooling setpoint, wall insulation thickness	Parametric study	EnergyPlus	Botswana	A combination of high internal loads and cooling set point may lead to the anti-insulation behaviour when higher insulation levels begin to yield higher cooling loads	[63]
Energy demand	Insulation thickness for each wall separately	Genetic alg.	EnergyPlus	China		[66]
Construction cost, heating energy cost	Structure of the internal partition walls	Parametric study	HTB2	Serbia	Glass-wool partition walls require minimal heating load and offer maximal lifecycle savings	[68]
Net present value, payback rate	Roof, wall and floor insulation levels	Parametric study	EC501	Italy	The optimal insulation configuration at the building level does not necessarily correspond to the optimal thermal transmittances calculated for the individual building components	[70]
Lifecycle energy savings	Wall insulation type, heating energy type, climate zone	Numerical	Heating and cooling degree days, P_1-P_2 method	Eight cities in Turkey		[72,73]
Energy fuel consumption	The growing media depth, leaf area index and irrigation of the green roof	Parametric study	EnergyPlus	USA		[74]
Heating load, cooling load	Leaf area index of the green roof, roof insulation	Parametric study	TRNSYS	Greece, France, Sweden	The green roofs are more suitable for retrofitting non- or poorly insulated existing buildings than for use in well-insulated new buildings	[75]
Lighting load	Orientation and height of external obstructing building blocks	Parametric study	EnergyPlus	Hong Kong		[76]
Heating load, cooling load	Orientation, size and distance of neighbouring houses, evergreen or deciduous trees	Parametric study	ESP-r	Canada	A neighbouring object on the south side has a larger impact on the heating energy demand, while the one on the west side has a larger impact on the cooling energy demand	[77]
Cooling load	Configurations and orientation of deciduous trees around the building	Parametric study	Energy balance integral equations	Portugal	The presence of trees can decrease the summer indoor air temperature by 3–4 °C in school buildings	[79]

buildings with poor roof insulation values, both in summer cooling and winter heating, making a strong case for green roof retrofit.

Knowing the amount of solar radiation available at a given location is a necessary prerequisite for the application of the passive solar measures. Ralegaonkar and Gupta [12] review models for the estimation of solar radiation, thermal simulation of passive solar buildings using scale models, software for calculating external and internal insulation of buildings as well as methods for the proper selection of shading devices, with particular focus on external static sunshades. It should be noted, however, that mostly pre-2002 articles are reviewed in [12].

Due to its transparency properties, a double skin facade admits a large amount of daylight in the building without a glare and allows a close contact between the building and its surroundings. Shameri et al. [13] review important aspects of designing double skin facades, such as the geometric parameters, glass selection, daylighting, shading, ventilation strategy, cavity depth and wind pressure, as well as their simulation and modelling, risk of overheating and fire safety concerns.

Quesada et al. [14,15] review the theoretical, experimental, developmental and feasibility studies of solar facades carried out during the last ten years. In [14] they review the opaque facades which cannot directly transfer solar heat gain into the building: building-integrated solar thermal, building-integrated photovoltaic, building-integrated photovoltaic thermal as active, and Trombe wall and solar chimney as the passive solar facades. In [15] they, on the other hand, review the transparent and translucent solar facades that do not only absorb and reflect the incident solar radiation, but can also transfer direct solar heat gain into the building: naturally and mechanically ventilated double skin facade, semi-transparent building-integrated photovoltaic and semi-transparent building-integrated photovoltaic thermal facade.

Hughes et al. [16] review the practice of implementing the common passive (night ventilation, wind towers) and active (split air conditioning, air handling units), as well as some complex (desiccant cooling and absorption cooling systems) cooling technologies in buildings. For each cooling technology, they provide a basic description and outline their features, factors and limitations.

Waqas and Din [17] review free cooling of buildings using phase change materials for cold storage. It is an emerging passive cooling technology, where the cool night air is used to solidify the phase change material in a separate storage medium, and the stored cold is extracted when needed during the hot daytime. The review discusses key issues and challenges faced in the design of free cooling systems, and contains a comprehensive list of the phase change materials, both those that are currently used and those that have the potential for use in free cooling systems.

2. Optimization methods for passive solar design strategies

The optimal design of buildings usually has to consider multiple and competing objectives such as simultaneous minimization of energy consumption, financial costs or environmental impact. Optimal solutions of such multiobjective design problems can be very different from each other. The Pareto front consists of those solutions for which no other solution is better for every objective simultaneously. This definition also implies that every non-Pareto solution is dominated by some solution from the Pareto front, while for any two solutions at the Pareto front holds that if one

Table 3
Summary of research on optimization of glazing and shading elements.

Objective function(s)	Design variables	Optimization method	Simulation method	Case study location	Major findings/limitations	Ref.
CO_2 emissions, cooling load, lighting load	Windows-to-wall ratio, horizontal overhang depth, the depth and the inclination of vertical fins, glazing type	Evolutionary neural networks	EnergyPlus	UK	The quality of the Pareto front is tested against the complete enumeration of the design space	[80]
Heating, cooling, lighting and ventilation load	Windows-to-wall ratio, window type, building plan type, heating/cooling setpoint combinations	Parametric study	IDA ICE	Sweden	A proper combination of glazing, shading and control setpoints in a fully glazed building may lead to only 15% increase in the energy consumption compared to the reference building with 30% windows-to-wall ratio	[81]
Heating, cooling, and lighting load	An array of two-state facade cells (each representing solid wall or a window)	Genetic alg.	EnergyPlus	USA	The window cells in optimal solutions are biased towards the top-west quadrant of the facade	[83]
Heating load, cooling load	Glazing type, windows size, presence of shading, building orientation, internal gains	Parametric study	TRNSYS	Italy		[84]
Heating load, cooling load	Windows-to-wall ratios, timber-frame macro-panel system type, building orientation	Parametric study	PHPP	Slovenia	The optimal windows-to-wall ratio for walls with very low U-values is smaller than in walls with higher U-values	[86]
Heating load, cooling load	Windows type, size and orientation	Parametric study	TRNSYS	Jordan, Germany	The heating load is highly sensitive to windows type and size as compared with the cooling load	[91]
Heating load, cooling load	Building aspect ratio, south windows size	Parametric study	SUNCODE-PC	Five cities in Turkey	The building aspect ratio has minor influence on energy performance compared to the south windows size in both cool and warm climates	[92]
Heating load, cooling load	Size and orientation of triple glazed, low-e windows	Parametric study	DEROB-LTH	Sweden	The size of the triple glazed, low-e windows in passive houses is more relevant for the cooling load, while it does not have a major influence on the heating load	[94]
Cooling load	Windows-to-wall ratio, frame-to-glazing ratio, glazing thermal transmittance, glazing solar transmittance, window orientation and external shading level	Parametric study	EnergyPlus	Greece, Cyprus, Portugal, Spain, Italy	The advanced fenestration products may actually increase the cooling load in warm climates, as their extremely low thermal transmittance prohibits the dissipation of the heat from internal gains to the outdoor environment	[97]
Heating load, cooling load	Window orientation, windows-to-wall ratio, office room width-to-depth ratio	Parametric study	EnergyPlus	USA	No window shading options were considered in the study	[98]
Heating load, cooling load	Louver inclination angle, louver-to-window area ratio, window orientation	parametric study	TRNSYS	Mexico, Egypt, Portugal, Spain, UK	If the louvers are not collected during the heating season to allow full window insolation then the total energy load may increase in climates like London	[102]
Heating load, cooling load	Louvers' slat tilt angle, depth-to-vertical-distance ratio	Parametric study	TRNSYS	Italy		[103]
Cooling load	Facade orientation, louvers' slat tilt angle, glass shading coefficient, height of light dimming sensor	Parametric study	IES-VE	Abu Dhabi	The use of dynamic louvers gives a very small margin over the optimal static louvers, not worth their extra cost and effort	[99]
Cooling load, construction cost	External shading device type, glazing type, building orientation	Parametric study	eQUEST	Singapore	The half egg-crate louver is most suitable for the southern and northern facades, whereas a horizontal projection with 30° downward tilt is most appropriate for the eastern and western facades	[104]
Cooling load	Blind colour, position within the double skin cavity, double-skin open/closed indicator	Parametric study	TAS	Belgium		[116]
Cooling load	Presence of shading, building position with respect to wind	Parametric study	TAS	Belgium	A single-sided day ventilation can reduce cooling needs by up to 30% in office buildings	[117]
Heating load, cooling load	Windows-to-wall ratio on urban level	Parametric study	LT method	London, Berlin, Toulouse	Highly overshadowed areas, such as the lower floors, require higher glazing ratios, while the optimal glazing ratios decreases with height	[119]
Energy-code compliant facade	Facade location, orientation, lightness, transparency, space use behind the facade, building depth	Interactive	EnergyPlus	Israel		[32]
Thermal comfort	Wall U-value, wall orientation, windows-to-wall ratio, shading device length	Parametric study	TAS, ESP-r, FLUENT	Singapore	Facade design guidelines are developed for Singapore	[106]
Heating load	Sunspace glazed-to-opaque surface area ratio, opaque wall and floor absorption coefficients, number of glass layers, sunspace orientation	Parametric study	DEROB-LTH	Jordan		[110]
Thermal comfort	Sunspace orientation, wall and floor absorption coefficients and heat capacities, ventilation rate, external shading system	Parametric study	DEROB-LTH	Italy		[111]
Windows energy balance	Window type, glazing area, window orientation	Parametric study	ASHRAE tables	Jordan		[85]
Windows energy balance (wintertime)	Building location, glazing type and orientation	Parametric study	Steady-state modeling	Eight major European cities	Only the triple low-e glazing guarantees net energy gains at south facades	[96]
Atrium energy balance	Glazing type, glazing surface area, skylight shape, atrium type, atrium interaction with adjacent spaces	Parametric study	ESP-r, ADELINE	Canada	Various atrium energy indicators are represented as functions of the glazing U-value and the solar heat gain coefficient	[112]

Table 3 (*continued*)

Objective function(s)	Design variables	Optimization method	Simulation method	Case study location	Major findings/limitations	Ref.
Atrium energy balance	Length-to-width ratio of atrium plan, skylight glazing type, glazing-to-roof ratio, atrium height	Parametric study	DOE-2	USA	Atrium should be a low rise structure with larger glazing-to-roof ratio in temperate and cold climates, while in hot dry and hot humid climates it should be a high rise structure with smaller glazing-to-roof ratio	[113]

objective is better met in one solution, then another objective must be better met in the other solution. The Pareto front thus reveals the trade-off relation between the two conflicting performance objectives, and helps the designer to appropriately choose one of the optimal solutions.

There is a large number of optimization methods in the literature, however, our goal is not to review the theory that they are based on (for such aspects, the reader is referred to the handbook [19]). We are interested, instead, in coupling the optimization methods with building energy simulations and their use in optimizing the passive solar design of buildings. There is already a significant body of literature on this topic and the number of published articles per year is shown in Fig. 1.

The coupling of an optimization method and an energy simulation software is illustrated in Fig. 2, which shows the process of generic building optimization with GenOpt [34]. GenOpt is first initialized with the description of building parameters, the simulation input template and the objective function. GenOpt then begins to automatically write the input files for the simulation program, run the simulations, collect the results and, based on the simulation results, determine the new set of input files for the next run, until the objective is met.

Moreover, since the use of optimization methods may be classified as still being in the early adoption stages among architects, the parametric studies are also reviewed in later sections. Parametric study is, actually, an elementary form of optimization in which, at each step, one or two of the parameter values are optimized, while the others are kept constant. While such a procedure does not necessarily yield a globally optimal solution, it still produces a locally optimal solution.

Baños et al. [20] review the computational optimization methods applied in solving the design, planning and control problems related to wind power, solar energy, hydropower, biomass, geothermal energy and hybrid systems. They conclude that the number of research papers that use optimization methods to solve renewable energy problems has increased dramatically over recent years, which is probably due to the continuous advances in both the theory of optimization and computational resources.

Caldas and Norford [21] review the basics of genetic algorithms, emphasizing the multi-objective optimization and the usefulness of the Pareto front search. Coupling the genetic algorithm with DOE-2 simulation engine [22], they present several applications, such as determining the composition of three-layered external walls and the size and placement of windows of an office building in the Phoenix and Chicago climates in order to optimize the operational energy use and the initial construction costs, or modifying the building form of a two-story structure with four equal-area square zones on each floor by manipulating the size and the shape and tilting the roof of each zone in order to optimize the trade-off between the lighting and heating energy.

Wang et al. [23] develop an object-oriented framework, coupled with the ASHRAE toolkit for building load calculations, implementing genetic algorithm to solve both single and multi-objective optimization problems. The framework determines the Pareto optimal solutions with the lifecycle cost and the lifecycle environmental impact as the objective functions (see Fig. 3). The design variables are the building's orientation, shape (rectangular and L-shape) and aspect ratio, wall types (concrete and steel-stud) and each wall's tilt from the vertical, the glazing types, the windows-to-wall ratio and the overhang depth. For the case study of an office building in Montréal, it turns out that, in the Pareto optimal solutions, the shape converges toward a rectangular shape with the aspect ratio about 0.40 and long side towards the south, the tilt of each wall converges to the lower bound of 75°, probably due to the reduced roof area in such case, and the windows-to-wall ratio on the north, east and west wall converges to the lower bound, while it varies for the south wall.

Christensen et al. [24] discuss BEopt, software designed to find the most cost-effective building designs by coupling the sequential search technique with the DOE-2 [22] and TRNSYS [25] simulation engines. Starting with the user-defined base case, the basic goal of BEopt is to find a net zero energy design: first, it reduces energy use by employing the energy efficiency options until it reaches the minimum annual cost, then it employs further energy efficiency options until the marginal cost of the saved energy equals the cost of producing photovoltaic electricity, from which point on, the energy savings become solely a result of adding photovoltaic capacity until the net zero energy design is found. The passive design input options are the building orientation, the U-values of walls, roof and floor, the thermal mass, the glazing type, the windows-to-wall ratio, the presence of overhangs and the infiltration rate, while the output contains detailed energy use and financial indicators for many optimal and near-optimal designs.

Tuhus-Dubrow and Krarti [26] compare three optimization methods: genetic algorithm, sequential search technique used in BEopt [27] and particle swarm optimization, with respect to their robustness, the ability to minimize the objective function, and efficiency, the number of simulations needed to reach the optimum. The tests are performed on a typical, detached single-family Building America benchmark home, and the objective function used is the annual cost of the mortgage for additional energy efficiency measures, plus utility bills. For a small design space consisting of a few design variables only, the sequential search technique slightly outperforms the genetic algorithm in robustness. However, the efficiency of genetic algorithm increases as the size of the design space increases. The results indicate that, when all of the available building envelope options in BEopt are used, the genetic algorithm outperforms the other two optimization methods by saving more than 50% of simulation efforts.

Bichiou and Krarti [28] develop a comprehensive energy simulation environment, an extension of the tool developed by Tuhus-Dubrow and Krarti [60], aimed to select building envelope features and heating and air conditioning system parameters yielding minimal lifecycle costs. The design variables include building's orientation, aspect ratio and shape, as illustrated in Fig. 4, insulation of floor, walls and roof, air-tightness level, glazing type, windows-to-wall ratio and depth of overhangs, thermal mass, heating and cooling setpoints and HVAC system type and efficiency. Three general optimization algorithms are implemented: the genetic algorithm, the particle swarm algorithm and the sequential search algorithm. The comparative analysis between them shows that the genetic algorithm and particle swarm

Table 4
Summary of research on whole building passive solar design optimization.

Objective function(s)	Design variables	Optimization method	Simulation method	Case study location	Major findings/limitations	Ref.
Construction cost	Building form factor and orientation, insulation level, windows-to-wall ratios, heating system type, solar thermal collector and photovoltaic system basic parameters	Genetic alg.	TRNSYS	Canada, USA	In cost-effective net-zero energy buildings, the climate mostly influences the southern windows area and the exterior wall type, while the building orientation mostly influences the overall windows area and the parameters of the active solar systems	[121]
Operating energy cost	Wall type, roof type, basement vs. slab, eaves depth, infiltration rate	BEopt	DOE-2	22 world locations	Among vernacular architectural traditions in nearly all locations, the optimal construction uses a thick packed earth or wood and earth wall	[126]
Heating load	External wall U-values, windows-to-wall ratios, building orientation	Parametric study	EnergyPlus	Wales		[122]
Heating load, cooling load	Building insulation level, airtightness, internal gains control, windows-to-wall ratios, ventilation strategy, thermal mass use	Parametric study	OPTI, TAS	Belgium		[123]
Heating load, cooling load	Insulation level, thermal mass, building aspect ratio, external wall colour, shading devices, window size, glazing type	Parametric study	EnergyPlus	Turkey		[125]
Heating load, cooling load	Wall thickness, roof and external wall insulation thicknesses, window orientation, windows-to-wall ratio, glazing type, sunroom depth/overhang depth	Orthogonal method, listing method	THERB	25 cities in China	A total of seven passive design zones are identified in China, within which the optimal combinations of passive design features are the same for each city	[128]
Heating load, cooling load, thermal comfort	Wall types, roofing, window glazing, window frame types, external shading device, infiltration rate, mechanical ventilation rate, HVAC system, thermostat settings, equipment power density	Parametric study	VisualDOE	Portugal		[141]
Heating load, cooling load, thermal comfort	Occupant behaviour type, building design type	Parametric study	EnergyPlus	Greece	In the context of climate change, building design is the key to thermal comfort optimisation, whereas the major mitigation potential for greenhouse gas emissions is related to the occupant behaviour	[143]
Cooling load	35 building design parameters	Monte Carlo analysis	EnergyPlus	Turkey	The total window area, the glazing U-value, the solar heat gain coefficient and the building aspect ratio have the most considerable influence on the energy performance of a building in a hot and humid climate	[127]
Cooling load	Insulation level, thermal mass, external wall colour, shading devices, window size, glazing type	Parametric study	TRNSYS	Hong Kong		[130]
Cooling load	Glazing type, blinds control, lighting control, night ventilation rate, lightshelf type	Parametric study	EnergyPlus	Israel	Complementing passive design strategies with active features yields largest energy savings, but using active features only cannot replace the benefits provided by passive design strategies	[144]
Cooling load	Insulation type, solar gain control option, external walls colour, natural ventilation strategy	Parametric study	IES-VE	Southeast England	For a predicted test reference weather year in the 2080s, the overheating problem could be addressed purely by passive means	[131]
Cooling load, lifecycle cost	Roof insulation, ventilation rate, glazing type, overhang shading depth, building orientation, aspect ratio, thermal mass	Parametric study	TRNSYS	Cyprus	Roof insulation and efficient window glazing are most cost effective measures in hot climates	[132]
Lifecycle cost, lifecycle environmental impact	Building orientation, shape, aspect ratio, wall type, wall tilt, glazing type, windows-to-wall ratio, overhang depth	Genetic alg.	ASHRAE toolkit	Canada	Optimal shape is rectangular with long side towards the south and minimal windows-to-wall ratios for non-south walls	[23]
Lifecycle costs	Building orientation, shape, aspect ratio, floor, wall and roof insulation, air-tightness, glazing type, windows-to-wall ratio, overhang depth, thermal mass, heating and cooling setpoints, HVAC system type and efficiency	Genetic alg. particle swarm sequential search	DOE-2	USA	Optimal solution reduces lifecycle costs by 10%–25%, has light thermal mass, low-e argon-filled windows and minimal windows-to-wall ratios for non-south walls	[28]
Lifecycle energy savings	Wall and roof insulation levels, colour of the asphalt roof shingles, window type, eaves presence, infiltration rate	BEopt+	DOE-2	Mexico	The existing design guidelines for temperate climate zones may actually increase energy consumption	[133]
Lifecycle energy use, CO_2 emissions	Building orientation, southern windows-to-wall ratio, wall insulation thickness, presence of overhangs, facade colour, eastern facade external shading, northern windows-to-wall ratio	Parametric study	EnergyPlus	Spain		[134]
Lifecycle cost, lifecycle environmental impact	Building orientation, aspect ratio, walls and roof structure, insulation levels, window types, windows-to-wall ratios	Genetic alg.	ASHRAE toolkit	Canada	The building aspect ratio converges to different values: to rectangle with longer side facing south for the minimization of lifecycle costs and to square for the minimization of the lifecycle environmental impact	[135]
Lifecycle cost	Windows-to-wall ratios, presence of shading, ceiling and walls thermal insulation thickness	Parametric study	TRNSYS	Jordan		[136]
Lifecycle cost, energy demand	Building orientation, wall and roof insulation thickness, windows-to-wall ratio, glazing type, air infiltration level, efficiency of lighting, appliances, heating and cooling system	Sequential search	DOE-2	Tunis	Optimal designs can cost-effectively reduce annual energy use by 50% compared to the current design practices in Tunisia	[137]

Table 4 (*continued*)

Objective function(s)	Design variables	Optimization method	Simulation method	Case study location	Major findings/limitations	Ref.
Lifecycle energy cost	Wall and roof insulation thicknesses, window types, shading depth, internal thermal mass wall thickness, night ventilation rate	GenOpt	IDA ICE	Australia	Optimal solution can cost-effectively reduce the space heating and cooling energy requirement by up to 94% compared to the current design practice in Sydney	[138]
Lifecycle costs	Wall, roof and floor insulation thicknesses, windows U-value, heat recovery unit type	GenOpt	IDA ICE	Finland	GenOpt results have been verified by comparison to the brute force search results	[139]
Retrofit cost	Wall, roof and floor insulation thicknesses, glazing type, space heating system, hot water production, solar collectors and photovoltaic panels investments	Parametric study	EN 832	Belgium	It is better to invest in insulation first, then in more energy efficient heating system, while renewable energy systems are the least profitable investment	[140]
Retrofit cost, energy savings, thermal comfort	External wall insulation, roof insulation, window types, solar collector installation	Tschebycheff procedure	TRNSYS	Portugal	Higher energy savings or lower retrofit cost do not necessarily lead to better thermal comfort	[33]
Retrofit cost, energy savings	External wall insulation, roof insulation, window types, solar collector installation	Tschebycheff procedure	RCCTE	Portugal	There exists a threshold up to which energy savings may be obtained with a small retrofit cost increase, while any further improvement requires a substantial retrofit cost increase	[35]

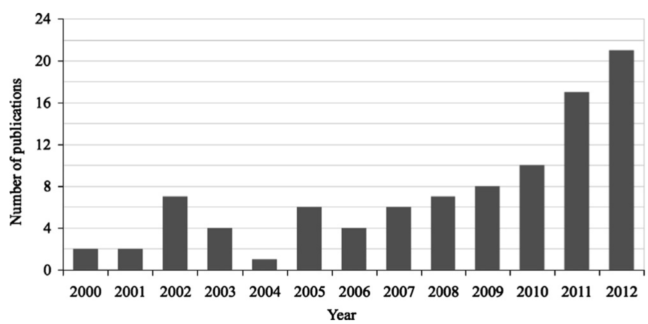

Fig. 1. Number of publications per year since 2000.

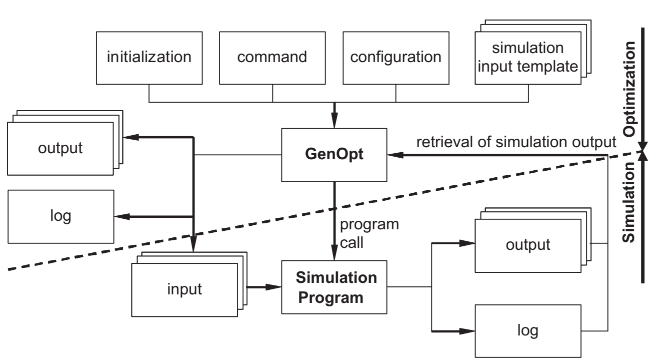

Fig. 2. Interface between GenOpt and a simulation program. Source: [18].

optimization typically require less computational time to reach optimal solutions than the sequential search algorithm. The case study of a single-family, Building America benchmark home model in five US locations: Boulder, Chicago, Miami, Phoenix and San Francisco, shows that the optimal selection can reduce lifecycle costs by 10%–25%, depending on the climate and the home type. Moreover, the lifecycle cost optimal solution in each of these locations turns out to have a rectangular form, light thermal mass, low-e argon-filled windows and the smallest feasible windows-to-wall ratio for east, north and west walls, while it varies for the south wall.

The building design strategies for the hot climates contrast those for the cold climates, with the main differences illustrated in Fig. 5. Attia et al. [29] develop a decision support tool ZEBO [30], based on EnergyPlus [31], to help to discover the parameters that would achieve a net zero energy building specifically for the hot climate of Egypt. The tool is contextual and based on an embedded benchmark model and database for the Egyptian residential buildings. Among the passive design strategies, the tool allows the input of orientation, zone dimensions, north and south window size and type, dimensions of the shading devices, wall type, and types and the thicknesses of wall and roof insulations. It also has the option to test the influence of each parameter on the building energy needs, but only for one parameter at a time.

Ochoa and Capeluto [32] develop an expert system NewFacades, a conceptual tool for designing energy-code compliant facades in the hot climates. It is coupled with EnergyPlus [31] for building energy simulation and suited for optimizing the facade design through the interaction with the user. The design variables are the facade's location, orientation, lightness and transparency, the envisaged use of space behind the facade and the building's depth and surroundings, while the system at the output suggests alternative facade solutions consisting of the wall U-value, the window size, the glazing type, the shading type and control, the lightshelf presence, the night ventilation rate and the lighting control. Its capabilities are demonstrated through a case study of an office building located in suburbs of Tel Aviv with the goal of determining an energy-code compliant facade maximizing west views towards the Mediterranean Sea.

Asadi et al. [33] develop a simulation-based scheme for optimizing the retrofit cost, energy savings and thermal comfort in the residential buildings during their retrofit. The scheme combines TRNSYS [25], GenOpt [34] and Tschebycheff procedure for multi-objective optimization, while the design variables represent a wide selection of alternatives for the external wall insulation, roof insulation, window types, as well as installation of a solar collector at the existing building. The case study of a semi-detached single family house in Portugal serves to clearly illustrate large differences in the optimal solutions depending on the choice of the objective function during optimization: retrofit cost, energy savings or percentage of discomfort hours, and to further show that solutions leading to more energy savings or lower retrofit cost do not necessarily lead to better thermal comfort.

In further study, Asadi et al. [35] introduce a multi-objective optimization model, based on the Tschebycheff procedure, with the minimum retrofit cost and the maximum energy savings as the competing objectives. The design variables include the external wall insulation materials, the roof insulation materials, the window types and the solar collector types, while the building energy

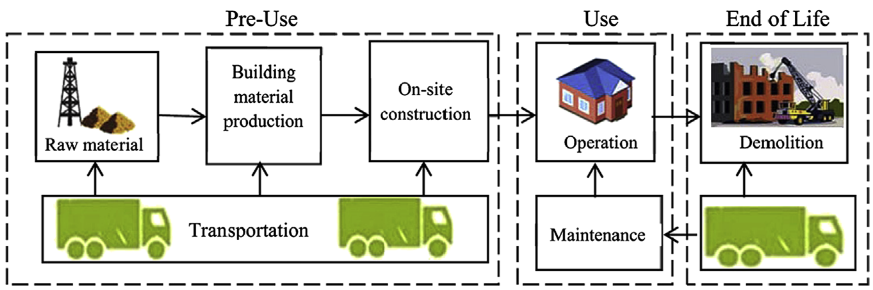

Fig. 3. Lifecycle of buildings. Source: [36].

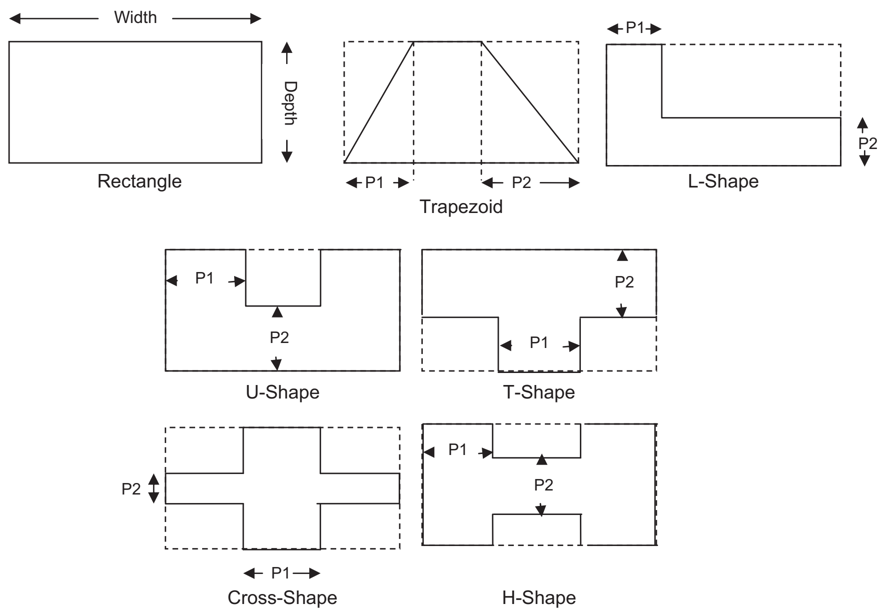

Fig. 4. Different building shapes considered in optimization studies. Source: [28].

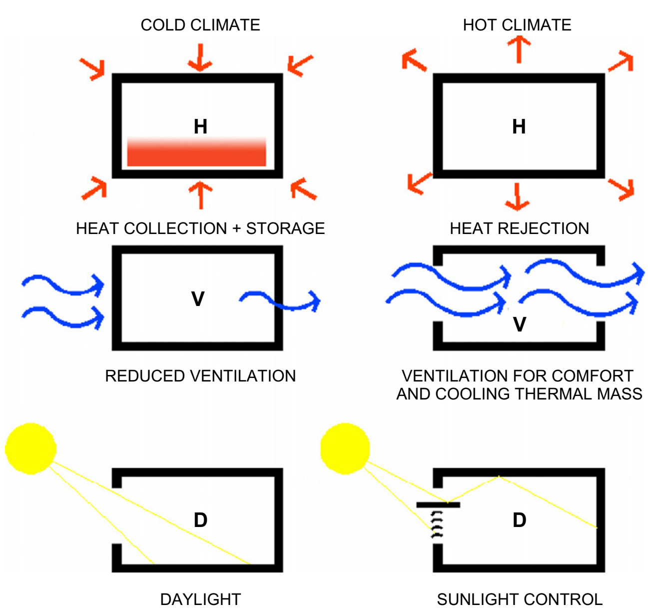

Fig. 5. Some building design strategies for cold and hot climates. Source: [144].

use is estimated by a simple thermal model based on the Portuguese building thermal code RCCTE. Using the same case study of a semi-detached single family house in Portugal as in [33], it is observed, after classifying the Pareto solutions by the energy classification code (into C, B- and B groups), that a small increase of the retrofit cost may lead to an improvement of the energy classification of the house from C to B-, while substantial investment is required to further improve its energy classification from B- to B.

Fesanghary et al. [36] develop a multi-objective optimization method based on the harmony search, a variant of stochastic random search, in order to minimize the whole lifecycle costs and the CO_2 emissions of the buildings. The design variables include the materials of the layers of the external walls, internal walls, floor, ceiling and roof, and the window types. The method enables to determine a series of Pareto optimal solutions for the case study of a single-family residential building located in Baton Rouge, USA, which help to understand the trade-off relation between the economical and environmental performance.

Tian [37] reviews the different sensitivity analysis methods used in building performance analysis: local analysis, regression, screening-based, variance-based and meta-model based methods. He discusses typical steps for implementing and a number of practical issues in applying sensitivity analysis methods, and gives a practical guidance on the choice, advantages and disadvantages of different sensitivity analysis methods in assessing building thermal performance.

Based on the design of experiments, a widely used statistical method that reduces the required number of experiments, Chlela et al. [38] start from a limited number of building simulation runs using the multizone building model SIMBAD [39], and create a metamodel that is able to quickly estimate energy consumption of each feasible parameter combination. The metamodel is developed

upon 13 parameters: the U-values of the walls, roof, floor and windows, the windows solar heat gain coefficients, the horizontal shading devices, the windows-to-wall ratio, the building thermal inertia, orientation, office internal heat gains, air-tightness and mechanical ventilation rate, with each parameter having one of five possible levels. The case study performed for an office building in three different locations in France: Nancy (cold climate), Agen (moderate climate) and Nice (hot climate), shows, however, that, while the obtained metamodels may be useful in obtaining good initial designs for the total energy demand, they may introduce significant errors for more complex outputs.

Hygh et al. [40] develop a multivariate linear regression model describing how energy use depends on 27 design parameters related to the building form, orientation, fenestration, shading and thermal envelope properties. The model is created for a rectangular, medium-sized office building located in one of four U.S. cities: Miami, Winston-Salem, Albuquerque and Minneapolis. For each of the four locations, the regression coefficients are obtained from EnergyPlus [31] simulations of 20,000 building variants, sampled by Monte Carlo simulation in order to exhaustively explore the building design space. The final regression model can be used as a meta-model that replaces the building energy simulation engine in the early design stages, in order to reduce the computational expenses and to draw attention to the parameters that are most likely to influence the energy performance of the building.

Petersen and Svendsen [41] introduce the cost of conserved energy model, a derivative of the net present value model, which serves to estimate the economic benefits of the individual energy-saving measures. Based on it, they give a simplified and transparent method for minimizing the total cost of the conserved energy, with the aim of determining a good initial design proposal that is expected to be near the economical optimum, which also yields a qualified estimate of an economically optimal energy solution. The method is applied to a case study of an office building, in which the parameters such as the building form, orientation, area, ceiling height and windows-to-wall ratio have been fixed, and the optimization has been limited to the wall, roof and floor insulation thickness, glazing type, lighting and ventilation rate, indicating which energy conserving measures among them deserve more attention in the early design stages.

Bouchlaghem [42] couples the optimization method with the admittance procedure to minimize the mean absolute deviation of the peak dry resultant temperature from the comfort level in an unconditioned building. The optimization method is a combination of the simple method and the nonrandom complex method, requiring the values of an objective function to be known at a number of grid points in the feasible region. The design variables determining this region are the building form aspect ratio, orientation, the thicknesses of the different layers of walls, roof and floor, ceiling height, the glazing type, the windows-to-wall ratio and solar heat gain factor, the shading type and the ventilation rate. In addition, seasonal optimization is implemented which readjusts the variables that are not fixed over the year—the shading devices and the ventilation rate.

Hoes et al. [43] evaluate the effect of the user behaviour on the energy performance of buildings, focusing on the question when is it useful to include advanced user behaviour models in the simulation process? In particular, they point out that the user behaviour has strong influence on the performance of heavily insulated buildings, as the internal heat gains are directly related to the user behaviour. They further develop the guideline to determine the appropriate level of the user behaviour modelling and conclude that more advanced user behaviour models should be used for buildings for which close details of the interaction of the user with the building are known. While this certainly gives directions for the future building energy research, such advanced user behaviour models are hardly employed in any of the studies reviewed here, as the details of the user interaction with the building are either unavailable or can widely vary. As an example of the last claim, Wymelenberg [44] reviews the patterns of occupant interaction with window blinds. It was observed that people appear to formulate their decisions about the blind position over a period of weeks or months, and not days or hours. A number of field studies revealed that only 5% of blinds are adjusted more than once per day, while 35% of blinds have not been changed over a period as long as four months and further 30% occupants self-reported as never adjusting the blinds. It is, thus, concluded that blind use is extremely personal and may not follow an easily definable model, which explains why blind use patterns are rarely used in the building energy simulations.

3. Optimization of particular passive solar design strategies

The passive solar design strategies are related to many building aspects, such as its form and orientation, insulation of walls, roof and floor, windows-to-wall area, glazing type, shading, etc. Reducing the number of passive solar design variables in optimization studies may help to more easily observe their relative impact on the building energy use.

3.1. Building form

Yi and Malkawi [45] introduce a representation of building forms by defining hierarchical relationship between geometry points, which allows a generation and control of the complex forms from a simple specification and, consequently, the exploration of the building geometry without being restricted to a simple form. The coupling of the genetic algorithm and EnergyPlus simulations [31] is used to minimize the heat flow across the building envelope as the objective function. The results of the case study show that the optimized building form, reducing the heating load per total volume for 12%, has slightly concave south, east and west surfaces, yielding more shaded surface areas during the summer, but not deep enough to generate shade in the winter period.

Capeluto [46] presents the model and algorithm for generating self-shading building envelope, based on the concept of solar collection envelopes. Its effectiveness in reducing cooling and lighting loads is demonstrated on a case study of an office building located in Jerusalem, Israel, through a parametric study in ENERGY [47] with facade type (vertical or self-shading), glazing type, presence of internal blinds and facade orientation as the design variables.

Adamski [48] discusses the optimization of the shape of a building consisting of two (northern and southern) parametrized semiovals, having vertical walls and windows, and constant volume and height. The objective functions are the minimum construction costs and the minimum heating load, and the optimization was performed theoretically, using the variational method. The theoretical study does not use a simulation engine, instead it uses the annual number of degree days and the average values of the total solar radiation falling during the heating season on the south, east and west vertical planes, to estimate the building heating load. The optimal solution consists of a semicircle in north and a parametrical curve, described by a complicated logarithmic function, in south. It is illustrated through a case study that such a form performs better than buildings with either a circular or a square base.

In a series of papers [49–51], Jedrzejuk and Marks describe the process of optimization of dimensions of an octagonal building,

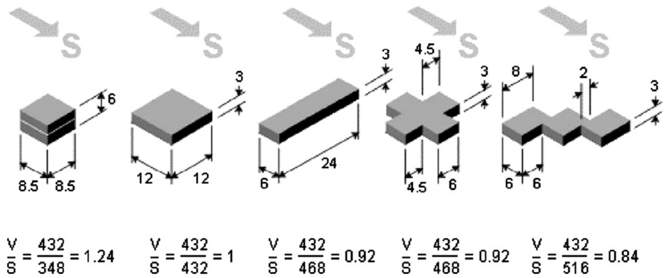

Fig. 6. The building shape coefficient illustration. Source: [123].

symmetric with respect to the north–south axis and having constant volume, where the objective function is a linear combination of construction cost, annual energy cost and emission of solid and gaseous pollution. The problem is described in [49] and the building shape design variables include the number of floors, the wall lengths, the wall inclination angles to the north–south direction, the wall U-values and the windows-to-wall ratios. The mathematical model describing heat losses and gains is presented in [50]. The optimization problem is solved theoretically for some of the design variables, while the rest are determined using numerical methods. The optimization method is illustrated in [51] on a case study of a residential building with 27 flats in the suburbs of Warsaw, Poland.

Kämpf and Robinson [52] describe a process of optimising building and urban geometric forms for the utilisation of solar irradiation, by coupling a hybrid evolutionary algorithm with RADIANCE [53] and a cumulative sky model for predicting solar irradiation. From the two case studies: a group of cuboid shaped buildings within an urban grid, and a building of rectangular plan whose roof has been parametrized as a Fourier series, it turns that the buildings/parts of the roof at the northern edge are all at maximum height, while the buildings/parts of the roof at the east and particularly south and west edges are irregular, in an apparent attempt to maximize solar access to south facing collecting surfaces.

Kämpf et al. [54] couple a multi-objective evolutionary algorithm with RADIANCE [53] in order to maximize the heating season solar irradiation offset by envelope heat losses by optimizing three different urban forms: Terraces Flat Roof, Slabs Sloped Roof and Terrace Courts. The design variables are the heights of facades and height and orientation of roofs. Details of Pareto optimal solutions are discussed for a case study of the center of Matthäus district in Basel, Switzerland.

Hachem et al. [55] study the effect of seven different building shapes: square, rectangle, trapezoid, L, U, H and T-shape on the solar radiation incident on the equatorial-facing facades using EnergyPlus simulations [31] for a case study of a two-story single family house located in Montréal, Canada. The design variables include the shape aspect ratio and the variations on the geometry of L and U shapes. The results indicate that solar radiation on non-convex shapes is significantly affected by the number of shading facades and the ratio of shading to shaded facade lengths, and that the reduction of this ratio and the increase of the angle enclosed between shading and shaded facades maximizes the solar potential.

Hachem et al. [56] investigate the energy demand of the two-storey single family housing units on a neighbourhood scale in Montréal, Canada. The design variables are two basic shapes (rectangle and L shape), orientation of individual units, two unit densities: medium-low consisting of detached units and medium-high consisting of attached units, and three site layouts characterized by the straight road, the south-facing curved road and the north-facing curved road. EnergyPlus simulations [31] reveal that the units in curved layouts generally have larger heating and cooling loads than in a straight road configuration, that attached units require up to 30% less cooling and 50% less heating than the detached configurations of the same site, and that arranging the units in south-facing rows may significantly affect the obstructed row, due to shading.

Depecker et al. [57] investigate a relation between the shape coefficient and the heating load of buildings. The shape coefficient is defined as the ratio between the external surface area and the inner volume of the building (see Fig. 6). The thermal behaviour of 14 hypothetical buildings, each built up from a different combination of eight cubes with side 5.4 m, is estimated using the in-house developed code, whose calculation method has the origin in the response factors method. The buildings are highly insulated, in accordance with current French building codes, and placed in two climates: the cold climate of Paris and the mild Mediterranean climate of Carpentras in southern France. As a result, the heating load in cold climate is almost directly proportional to the shape coefficient due to weak heat gain from solar radiation through glazing. On the other hand, opaque wall surfaces have less importance in mild and sunny climate and no correlation between the heating load and the shape coefficient is observed.

Albatici and Passerini [58] introduce another index, the south exposure coefficient, defined as the ratio of the area of the south walls to the building volume, to explain the relationships between the building shape and heating load in mild and sunny climates. They consider building models consisting of 16 base modules and calculate heating loads according to EN ISO 13790:2008 for four Italian cities: Canazei and Trento in the Alpine region, Florence and Rome. The case study confirms the results of Depecker et al. [57] that the shape coefficient is more important in cold localities, but show that the south exposure coefficient is the proper index to be used in mild and warm climates.

Ouarghi and Krarti [59] use a combination of the neural networks and genetic algorithm to select an optimal building shape to minimize the total building annual energy cost as well as construction costs. The energy use for an arbitrary building shape, with a predefined building volume, is estimated from the energy use of a rectangular building having equal perimeter. The Bayesian neural networks are first used to create an approximate model for predicting the energy use through a training process, which uses DOE-2 simulation engine [22] to estimate energy use for specific design configurations of a typical office. The genetic algorithm then uses the created approximate model in the optimization step, in order to reduce computational time. The models are created for four locations: Cairo, Gabes, Rome and Tunis, while the design variables used in optimization are the building's relative compactness, the walls and roof insulation levels, the windows-to-wall ratio and the glazing type.

Tuhus-Dubrow and Krarti [60] couple genetic algorithm to DOE-2 simulation engine [22]. The basic structure of this coupling is shown in Fig. 7. The goal of the study is to minimize the energy use and lifecycle cost for a Building America benchmark home model in five US cities: Boulder, Phoenix, Chicago, Miami and San Francisco. The shape design variables include the building shape: rectangle, trapezoid, L, T, cross, U or H-shape, its orientation and the geometric aspect ratio, while the remaining design variables include wall, roof and floor insulation levels, windows area, glazing type, infiltration rate and thermal mass. Two separate optimizations are performed: in the first, only the building shape design variables vary and the remaining design variables are taken from the benchmark model, while in the second, all the design variables are allowed to vary. In the first optimization, trapezoid shape performs best—for the heating dominated climates, the south facing trapezoid improves passive heating performance due to the presence of southeast and southwest facing windows. In the

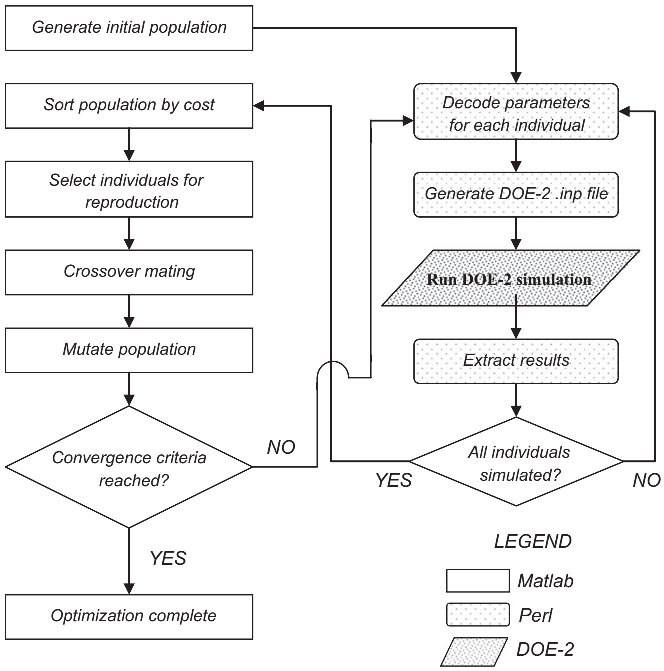

Fig. 7. Flowchart diagram of coupling of genetic algorithm with the DOE-2 simulation engine. Source: [60].

second optimization, however, the square is the optimum shape for every climate, indicating that other design variables have more impact on building energy use.

Wang et al. [61] present a general methodology to optimize the building shape with the lifecycle cost and the lifecycle environmental impact as the two objective functions, by coupling the genetic algorithm, employing the elitist strategy, with a simulation program developed in one of the authors' PhD thesis. The building footprint is represented by a simple n-sided polygon with no intersection of nonconsecutive edges, and besides the shape description, the design variables include two alternative structural systems, insulation levels, glazing type, windows-to-wall ratio and overhang presence, depth and height above windows on each facade. Multiple Pareto optimal solutions have been found for a case study of a multi-story office building of pentagonal shape, located in Montréal, Canada. It is observed that the building footprint takes different shapes for the Pareto solutions: the solutions with lower lifecycle cost have shapes close to the regular polygon, while the solutions with lower lifecycle environmental impact have larger edge length on the south facade.

3.2. Opaque envelope components

Chesné et al. [62] study the relationship between the insulation thickness and the bioclimatic margin of a building, defined as the gap between the potential of passively using solar energy and the building heating energy needs. Parametric study of the influence of adding various thicknesses of insulation to a noninsulated case study building in Trappes, France, reveals that the first few centimeters of insulation have most significant influence on both the decrease of the heating energy needs and the increase of the bioclimatic margin, and that these changes progressively become very small and fall below 1% after certain insulation thickness, yielding another criteria for choosing the optimum insulation thickness.

Masoso and Grobler [63] show, through a parametric study of a case study building in Gaborone, Botswana, that a combination of high internal loads and cooling set point may lead to the anti-insulation behaviour of a building during the cooling season, when higher insulation levels begin to also yield higher cooling loads. The design variables in the study are the cooling set point and the thickness of external wall insulation, while the cooling load has been estimated by EnergyPlus [31] and validated on a physical model.

Oral and Yilmaz [64] develop a theoretical argument for determining the maximal feasible U-values for walls which ensure thermal comfort, while minimizing the heating load. The limit U-value of each wall depends on the building's form, represented as the ratio of the total facade area to the building volume, glazing type, windows-to-wall ratio and the wall orientation. The case study is performed for three Turkish cities: Istanbul, Ankara and Erzurum, representing temperate humid, temperate dry and cold zones with long and intensive heating periods. Further parametric study for Erzurum is presented in [65].

Shi [66] uses modeFRONTIER optimization environment [67], coupled with EnergyPlus [31], to find the best strategy to minimize the space conditioning load and reduce the insulation usage at the same time. The design-of-experiment methods are used to create the initial population of designs which exhaustively samples the design space, after which modeFRONTIER applies genetic algorithm to generate the Pareto front in a reasonable number of runs. As a case study, it was used to optimize the thicknesses of the insulation on the six walls of an office building in Nanjing, China.

Bojić et al. [68] perform a parametric study on the case study of a typical small house in Belgrade, Serbia, to determine the impact of the structure of the internal partition walls on energy consumption by predicting the annual heating load and power of radiators with HTB2 building simulation software [69]. By comparing the investment costs, heating costs and lifecycle costs for six different partition wall types, they obtain that a house with glass-wool partitions requires minimal heating load and offers maximal lifecycle savings.

Lollini et al. [70] determine the optimum roof, wall and floor insulation levels with respect to the net present value and the payback rate as the objective functions, first on the component level by theoretical argument, then on the building level by parametric study. The case study includes a single family house and a tower building, as buildings with extreme envelope surface area/volume ratios, located in six Italian climatic zones (in Lampedusa, Palermo, Latina, Lucca, Arezzo, Milan, Sondrio, Bressanone), with heating energy loads estimated by EC501 software [71], based on the Italian legislative framework. They find critical transmittance values for each of the climate zones and also note that the optimal insulation configuration at the building level does not necessarily correspond to the optimal thermal transmittances calculated for the individual components.

In two studies, Ucar and Balo [72,73] determine the economically optimum thickness of the external wall insulation for four different insulation materials, five different heating energy types and cities in four climate zones of Turkey. First, in [72] they study the impact of the insulation thickness in a sandwich wall on the lifecycle costs in Ağri, Elaziğ, Kocaeli and Aydın and in the second study [73], they determine the optimum insulation thickness in Mersin, Elaziğ, Şanlıurfa and Bitlis. The building energy consumption in both studies is estimated using the heating and cooling degree-days, and the P_1–P_2 method is used to calculate the amount of the net energy savings. The economically optimal insulation thickness, yielding the maximum net energy savings, is obtained by using MATLAB's Optimization toolbox and the appropriate insulation material/heating energy type combinations are further discussed for each of these cities.

Green roofs protect the roof structure from the extreme temperatures and large temperature fluctuations. Sailor [74] develops a physically based model of the energy balance of a

vegetated rooftop and integrates it into EnergyPlus [31], as an ecoroof option for the outer construction layer. The implemented model enables setting up growing media thermal properties and depth, vegetation characteristics such as plant height and leaf area index, and soil moisture conditions such as stomatal conductance, irrigation and precipitation. Parametric study is performed for a case study of an office building, located in Chicago and Houston, USA, evaluating the role of the growing media depth, leaf area index and irrigation on the natural gas and electricity consumption.

Jaffal et al. [75] implement in TRNSYS [25] a mathematical model of green roof's thermal behaviour, based on the Sailor's approach [74], and perform a parametric study quantifying its impact on building energy performance with respect to the leaf area index and roof insulation, for a case study of a single family house located in Athens (Greece), La Rochelle (France) and Stockholm (Sweden). The results show that the impact of a green roof on the cooling demand decreases as the roof insulation level increases, implying that green roofs are more suitable for retrofitting non- or poorly insulated existing buildings than for use in well-insulated new buildings.

Li and Wong [76] aim to develop proper daylighting schemes for densely populated urban areas, where high-rise buildings constructed close to each other play a significant role in daylighting design, through a parametric study with EnergyPlus [31] on electricity reduction from daylighting of a high-rise building's perimeter zones. The case study building is located in Hong Kong, and the design variables are the orientation and the height of external obstructing building blocks. They further derive correlations between the electricity reduction and the obstruction angle using regression techniques.

Nikoofard et al. [77] quantify the effects of shading by neighbouring houses, evergreen or deciduous trees on the annual heating and cooling energy demand of the residential buildings, by performing a parametric study in ESP-r [78] with orientation, size and distance of neighbouring objects as the design variables, for a case study of a two-storey detached house, located in Halifax, Toronto, Calgary and Vancouver, representing major climatic regions in Canada. The results indicate that the heating energy demand may increase by up to 10%, while cooling energy demand may decrease by up to 90%, and that a neighbouring object on the south side has a larger impact on the heating energy demand, while the one on the west side has a larger impact on the cooling energy demand.

Conceição and Lúcio [79] study the influence of the presence of opaque external trees with pyramidal shape on the thermal behaviour of a building in summer conditions, using as a case study a school building located in Faro, Portugal. Since the correctly dimensioned horizontal shading devices are used for south windows, the parametric study deals with the configurations of deciduous trees used for shading windows of west, south-west, east and north-east orientation. It is shown that the presence of trees can decrease the indoor air temperature by 3–4 °C.

3.3. Glazing and shading

While fenestration is important for adding aesthetics to the building design and providing adequate daylight illumination levels, it also plays a vital role for the thermal comfort in buildings, and is easily considered as the most important individual strategy in passive solar design of buildings.

Zemella et al. [80] couple the evolutionary neural networks with EnergyPlus [31] with the goal of optimizing the design of the typical facade module. They apply it both in single-objective optimization which minimizes the annual amount of CO_2 emissions due to energy consumption for heating, cooling and artificial lighting, and in multi-objective optimization determining the Pareto front for the conflicting objectives of energy consumptions for cooling and for artificial lighting. The design variables are the windows-to-wall ratio, the depth of horizontal overhang, the depth and the inclination of vertical fins and the glazing type. The quality of the Pareto front, found by the presented approach, is tested against the complete enumeration of the design space in a case study of a facade module for the west elevation of an office building located in London.

Poirazis et al. [81] perform a parametric study of a typical single skin, six storey, late 1990s office building located in Gothenburg, Sweden, in order to study the influence of facade construction and plan type on the energy use for heating, cooling, lighting and mechanical ventilation. The design variables include the windows-to-wall ratio (30%, 60%, 100%), seven window types, two plan types (open plan and cell plan) and three heating/cooling setpoint combinations, while the building energy use is simulated using IDA ICE [82]. The results are exhaustively discussed, and it is observed that a proper combination of glazing, shading and control setpoints may lead to only 15% increase in the energy consumption of fully glazed buildings, compared to the reference building having 30% windows-to-wall ratio.

Wright and Mourshed [83] couple the genetic algorithm with EnergyPlus [31] to optimize fenestration of a building facade with respect to the energy use for heating, cooling and lighting. The building facade is divided into a number of cells, each of which is an individual design variable with two possible states: solid wall or a window. The case study of a southern facade of an atrium of a three-storey commercial building located in Chicago, USA, shows that, while optimal solutions yield interesting and innovative architectural forms, the window cells in them are biased towards the top-west quadrant of the facade, both for unconstrained and constrained cases.

Gasparella et al. [84] study the influence of windows type and size on the heating and cooling energy needs and peak loads for a case study of a well-insulated single-family, two storey house located in Milan, Italy. The parametric study is first performed with TRNSYS [25], with glazing type, windows size, presence of shading, building orientation and internal gains as the design variables, after which multiple linear regression is used to reveal the most influencing parameters.

Hassouneh et al. [85] evaluate the influence of windows on the energy balance and determine the optimal energy savings for a case study of a residential building located in Amman, Jordan. The parametric study is performed using the self-developed Excel-based software using the ASHRAE tables of solar heat gain and cooling factors of glass, and the design variables are window type, glazing area and window orientation.

Leskovar and Premrov [86] study the optimal windows-to-wall ratios minimizing the total annual heating and cooling load for a case study of a two-storey house with prefabricated timber-frame structural system, located in Ljubljana, Slovenia. The house is well-insulated with opaque envelope elements having U-value between 0.102 and 0.135 $Wm^{-2} K^{-1}$, using triple low-e glazing, overhangs on the south and external vertical shading devices on the west and the east facades. The parametric study is performed in PHPP [87] with the design variables being the windows-to-wall ratios at each facade, three timber-frame macro-panel systems and the building orientation. The results indicate that the optimal windows-to-wall ratio for walls with very low U-values is smaller than in walls with higher U-values, and the authors derive a linear interpolation predicting approximate energy demand based on the wall U-value and the windows-to-wall ratio. It is interesting that almost identical parametric study was published by the same authors also in [88–90].

Jaber and Ajib [91] in a parametric study performed with TRNSYS [25] determine the effects of the windows type, size and

orientation on the annual heating and cooling energy demand of a case study of a single-story house located in three different climate zones: Amman and Aqaba in Jordan and Berlin in Germany. Optimal parameter combinations are identified for the lifecycle cost as the objective function. The results indicate that the heating load is highly sensitive to windows type and size as compared with the cooling load.

Inanici and Demirbilek [92] aim to determine the optimum building aspect ratio and south window size which minimize the total annual heating and cooling load of apartments at intermediate floors in residential buildings, with no roof or ground contact, for five cities in Turkey: Erzurum, Ankara, Diyarbakir, Izmir and Antalya. The parametric study is performed in SUNCODE-PC software [93]. The results show that the building aspect ratio has minor influence on energy performance (with differences at most 3%–6% for the same south window size), while the increase of south window size leads to the decrease of the total annual load in cool climates (Erzurum and Ankara) and its increase in warm climates (Diyarbakir, Izmir and Antalya).

Persson et al. [94] evaluate the influence of the size and orientation of the triple glazed, low-e windows on the heating and cooling energy loads on a case study of 20 terraced passive houses built in Gothenburg, Sweden. The parametric study is performed with DEROB-LTH [95] dynamic building simulation tool, and the design variables include windows size and orientation. The results show that the size of triple glazed, low-e windows does not have a major influence on the heating load, due to the extremely well-insulated walls and the efficient ventilation system, but it is relevant for the cooling load. The optimal solution has smaller window area facing south and larger window area facing north when compared to the already built houses, showing that in passive houses, it is not necessary to keep down the window area facing north.

Manz and Menti [96] theoretically develop simple design charts, based on a steady-state modeling, that show the impact of the local climate, the glazing quality and the facade orientation on the ratio of solar gains to thermal losses in wintertime. The method is exemplified in a parametric study whose design variables are the glazing type, glazing orientation and the location (Bucharest, London, Madrid, Moscow, Rome, Stockholm, Warsaw and Zurich, representing the diversity of European climates). The results show that only the triple low-e glazing guarantees net energy gains at all locations at south facades, while the conventional double and single glazings lead to net losses at all facades, except for most southern locations.

Tsikaloudaki et al. [97] study the cooling performance of windows in office buildings in the Mediterranean region through parametric studies with EnergyPlus [31] of a typical office module with moderate level of wall insulation, located in Athens (Greece), Larnaca (Cyprus), Lisbon (Portugal), Malaga (Spain) and Rome (Italy). The design variables are the windows-to-wall ratio, frame-to-glazing ratio, glazing thermal transmittance, glazing solar transmittance, window orientation and level of external shading. Focused on discussing results for Athens, they notice that advanced fenestration products may increase cooling load, as their extremely low thermal transmittance prohibits the dissipation of the heat from internal gains to the outdoor environment.

Susorova et al. [98] evaluate the role of geometric factors of fenestration on energy performance of an office building for six US cities in distinct climate zones: Houston (hot climate), Los Angeles (warm climate), Seattle (mixed climate), Chicago (cool climate), Minneapolis (cold climate) and Duluth (very cold climate), through a parametric study in EnergyPlus [31]. The design variables are the window orientation, the windows-to-wall ratio and the office room width-to-depth ratio. They develop guidelines for the proper combination of the windows-to-wall ratio and the office width-to-depth ratio for each climate type, but these guidelines should be taken with caution, as no window shading options were considered in the study.

Hammad and Abu-Hijleh [99] explore the influence of external louvers on the energy consumption of an office building located in Abu Dhabi, UAE, implemented both as an active, movable system and as a static system. The design variables for the parametric study include the height of light dimming sensor, glass shading coefficient, slat tilt angle of louvers and facade orientation, while energy consumption is predicted with IES-VE software [100]. Although the use of dynamic louvers achieves maximum reduction in energy consumption, it has a very small margin over the optimal static louvers configuration, suggesting that investing in the dynamic louvers is not worth the extra cost and effort.

Sherif et al. [101] study the influence that the depth ratio and perforation percentage of the external fixed deep wooden solar screens have on decreasing the annual energy loads in the hot and arid desert environments. They find the optimum depth/perforation configurations for south, west, north and east window orientations in a parametric study with EnergyPlus [31] for a typical residential building located in El-Kharga Oasis, Egypt. The results indicate that the optimal solar screens in the south and west orientations could achieve energy savings up to 30% of the annual energy loads, and that they are more efficient than the traditional ones.

Palmero-Marrero and Oliveira [102] study the effect of the horizontal and vertical louver shading devices on the cooling and heating energy loads for a case study of a residential building located in Mexico City, Cairo, Lisbon, Madrid and London, where the horizontal louvers are used for south facade, and vertical louvers for east and west facades. The parametric study is performed in TRNSYS [25], and the design variables are louver inclination angle, louver-to-window area ratio and window orientation, The results show that, for optimal parameter values, the cooling energy load is decreased in each location, however, if the louvers are not collected during the heating season to allow full window insolation then the total energy load may actually increase in climates like London.

Datta [103] optimizes the external fixed horizontal louvers used on the south window with respect to the annual primary energy demand for a case study of a single-story house located in Italian cities of Milano, Rome, Napoli and Palermo, through parametric studies performed with TRNSYS [25] with the louvers' slat tilt and the depth-to-vertical-distance ratio as the design variables.

Chua and Chou [104] determine the optimal combination of external shading device and glazing types for cost-effective reduction of the cooling load for two case studies of high-rise residential buildings, located in Singapore. The parametric study is performed in eQUEST [105] and the design variables are nine external shading device types, four glazing types and two building orientations. The results show that the half egg-crate louver is most suitable for the southern and northern facades, whereas a horizontal projection with 30° downward tilt is most appropriate for the eastern and western facades.

Liping et al. [106] perform two parametric studies for facade optimization of naturally ventilated residential buildings in Singapore. First, they study the influence of the U-value, the windows-to-wall ratio and the shading device length at differently oriented external walls on the difference between the mean radiant temperature and the indoor ambient temperature, using TAS [107] as the simulation engine. After establishing appropriate U-values of external walls, they further study thermal comfort distribution for all combinations of the windows-to-wall ratios and the shading device lengths for differently oriented walls using coupled simulations between ESP-r [78] and CFD simulation tool

FLUENT [108]. The facade design guidelines for Singapore are then developed based on the results of these parametric studies.

Zinzi et al. [109] study the effect of using cool painted aluminum window shutters on the cooling energy. Cool paints have increased solar reflectance in the near infrared range of the spectrum, while being able to reproduce design colour in the visible range. The parametric study with EnergyPlus [31] which quantifies the net energy demand for a cooled, and the thermal comfort conditions for a free running house, located in Palermo in southern Italy, Rome in central Italy and Venice in Northern Italy, shows that cool painted shutters yield 3.2%–7.1% relative energy savings over the conventional ones, and that they are most effective in reducing the extreme indoor operative temperatures.

Bataineh and Fayez [110] study the effect of attaching sunspace to a living room on the heating load in a case study of a residential building located in Amman, Jordan. The design variables are the glazed-to-opaque surface area ratio, opaque wall and floor absorption coefficients, number of glass layers and sunspace orientation, while the energy simulations are performed with DEROB-LTH [95]. The effects of using night ventilation and daytime curtain shading to prevent summer overheating are quantified as well.

Oliveti et al. [111] evaluate and discuss solar gains and operative temperature of non-air-conditioned sunspace bordered by two air-conditioned rooms, one adjacent and another below, in a parametric study performed with DEROB-LTH [95] for three Italian cities: Cosenza, Rome and Milan. The design variables are the sunspace orientation, the absorption coefficients and heat capacities of the vertical wall and the floor, ventilation rate and external shading system.

Laouadi et al. [112] study the thermal and energy performance of atriums in a parametric study with the glazing type, glazing surface area, skylight shape, atrium type, and atrium interaction with adjacent spaces as the design variables. Simulated atriums are four-story buildings with the ground-to-roof height of 16 m, located in Ottawa, Canada, and the thermal and energy simulations are performed with ESP-r [78] and ADELINE [114]. Estimated seasonal solar heat gain, cooling and heating peak load, annual cooling, heating and total energy are further represented as linear or quadratic functions of glazing's U-value and solar heat gain coefficient using regression techniques.

Aldawoud [113] discusses the effects of the atrium geometry factors on the energy savings through a parametric study in DOE-2 [22] for four US cities: Phoenix (hot dry climate), Miami (hot humid climate), Chicago (temperate climate) and Minneapolis (cold climate). The atrium is bounded by the facts that its skylight is the only access point to the exterior environment, with its exterior walls being adiabatic. The design variables are the length-to-width ratio of atrium plan, the skylight glazing type, the glazing-to-roof ratio and the atrium height (in stories). The results show that the square-shaped atrium has best performance. Atrium offers more energy savings as a low rise structure with larger glazing-to-roof ratio in temperate and cold climates, while in hot dry and hot humid climates it should be a high rise structure with smaller glazing-to-roof ratio.

Garcia-Hansen et al. [115] study the effects of using skylights, roof monitors and clerestory roof windows in spaces without an equator-facing facade on the heating load, ventilation and daylighting in cold to temperate climates. The case study is a 42 m^2 room connected to the exterior by a roof, located in Malargüe, Argentina. The design variables are the type and arrangement of roof openings and thermal mass of the room. While no important variation is observed for the thermal performance of skylights, clerestory roof windows and roof monitors, it turns out that roof monitors yield best results for daylighting under variable sky conditions and best combined results for thermal and daylighting effects.

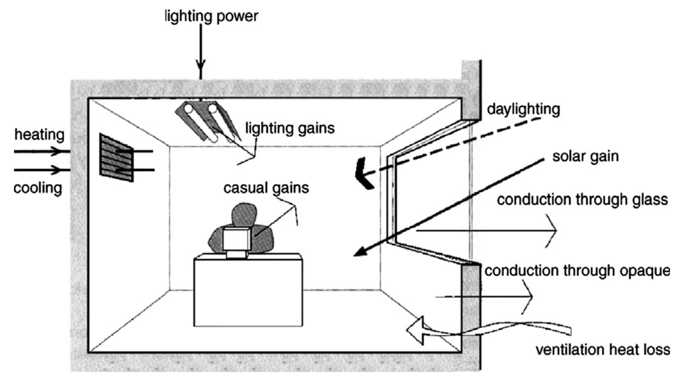

Fig. 8. Energy flows considered by the LT method within a unit cell 3 m × 3 m × 6 m. Source: [118].

Gratia and Herde [116] perform a parametric study in TAS [107] for an office building with a double-skin facade, located in Louvain-La-Neuve, Belgium, in order to examine the influence of the position and the colour of the blinds on the cooling load. The design variables are the blinds colour, position within the double skin cavity, and the indicator whether the double-skin facade is open or closed. The cooling load is quantified and discussed in detail for each case.

Gratia et al. [117] perform a parametric study with TAS [107] to determine the size and location of window apertures in order to reach the sufficient rates of natural ventilation in narrow office buildings. The design variables are the presence of shading and the building position with respect to wind (protected from wind, wind perpendicular to the openings, wind parallel to the openings). The case study of an office building located in Uccle, Belgium, performed for a typical sunny summer day reveals that a single-sided day ventilation can reduce cooling needs by up to 30%.

Ratti et al. [119] use the digital elevation model to develop ways to estimate the surface-to-volume ratios on a city scale and couple them with LT method [120], which predicts the energy flows within a unit office cell (see Fig. 8), to explore the effects of the urban texture on building energy consumption. The case study of the optimum glazing ratio, corresponding to the minimum energy consumption, in the central areas of London, Berlin and Toulouse (all simulated under the climate of London) reveals the variation of the optimum glazing ratio with height: highly overshadowed areas (for instance, the lower floors) require higher glazing ratios, while glazing ratios decrease with height, with a pattern that repeats itself in all cities.

4. Whole building passive solar design optimization

The aim to simultaneously optimize a more comprehensive set of passive solar design strategies, with the goal of optimizing whole building's passive behaviour, easily leads to the design spaces that may be prohibitively large for available computational resources. The researchers, therefore, need to find a proper balance between a number of feasible values for each of the design variables and the ability to observe the relative impact of different parameters on the building energy use. Thus, parametric studies dominate this section.

Charron [121] uses genetic algorithm optimization tool linked to TRNSYS [25] to search for the cost-effective net-zero energy residential building designs. The design variables, among the passive measures, include the building form factor and orientation, the insulation level and the windows-to-wall ratios for the external walls, and among the active measures, the heating system type and the basic parameters of the solar thermal collector and

photovoltaic systems. For the case study of a residential building in four locations: Montréal, Nanaimo and Iqaluit in Canada and Sacramento in USA, the results indicate that, among cost-effective optimal solutions, the climate mostly influences the south window coverage and the exterior wall type, while the building orientation mostly influences the overall windows area and the parameters of the active solar systems.

Wang et al. [122] investigate the feasibility of achieving a zero energy house design in Cardiff, UK. They first identify the optimal passive facade design minimizing heating energy load through a parametric study with EnergyPlus [31] in which the design variables are the U-values of external walls, windows-to-wall ratios and building orientation. They further use TRNSYS [25] to simulate the performance and properly size the solar hot water system, underfloor heating system, photovoltaic system and wind turbine, concluding that it is theoretically possible to achieve the zero energy homes in the UK.

Gratia and Herde [123] aim to develop guidelines for designing energy-efficient office buildings in the Belgian climate with respect to the building insulation level, airtightness, internal gains control, the windows-to-wall ratios for different external wall orientations, ventilation strategy and thermal mass use, through the extensive discussion of the results of several parametric studies performed with OPTI [124] and TAS [107] on the case studies of two office buildings located in Uccle, Belgium.

Eskin and Türkmen [125] in a parametric analysis investigate the effect of passive design strategies: insulation and thermal mass, building aspect ratio, external wall colour, shading devices, window size and glazing type on the cooling and heating loads, estimated by EnergyPlus [31], of an office building in Turkey. The study is performed for cities in four major climatic zones in Turkey —hot summer and cold winter (Ankara), mild climate (Istanbul), hot summer and warm winter (Izmir) and hot and humid summer and warm winter (Antalya).

Zhai and Previtali [126] review energy-saving implications of the vernacular architectural traditions, which have been shaped through a long period of trial and error and the ingenuity of local builders who possess specific knowledge about their place on the planet. They further use BEopt simulation and optimization tool [27], based on the sequential search technique, to identify optimal constructions using ancient vernacular building techniques for a case study located in 22 places selected in 11 of the world's climate zones. The design variables are the wall type, roof type, basement vs. slab, eaves depth and infiltration rate, while the objective function is the operating energy cost. It is interesting that in nearly all locations, the optimal construction uses a thick packed earth or wood and earth wall. Even though it has a lower overall insulation value, it appears to be selected because of its thermal storage capacity, demonstrating the value of thermal mass in improving energy performance in all climates.

Yıldız and Arsan [127] use the Monte Carlo analysis, coupled with EnergyPlus simulations [31], to determine the most significant parameters of energy performance among 35 parameters related to building design, HVAC and lighting for buildings in hot-humid climates by considering an existing 10-storey apartment building in Izmir, Turkey. The study indicates that the total window area, glazing U-value, its solar heat gain coefficient and the building aspect ratio have the most considerable influence on the energy performance.

Gong et al. [128] aim to minimize energy consumption of a simple box model with a window and without internal heat sources for 25 representative cities in China by finding the optimal combinations of seven passive design measures: wall thickness, roof and external wall insulation thicknesses, window orientation, windows-to-wall ratio, glazing type and sunroom depth/overhang depth. The optimization process first employs the orthogonal method to analyze the significance of each parameter and their interactions on energy consumption, as estimated by THERB [129], and then uses the listing method to find optimal parameter combinations. As a result, the authors identify a total of seven passive design zones of China, within which the optimal combinations of passive design features are the same for each city.

Cheung et al. [130] discuss the effect of passive design strategies: insulation and thermal mass, external wall colour, shading devices, window size and glazing type on the annual cooling energy and peak cooling load, estimated by TRNSYS [25], through a parametric analysis of an apartment in a high-rise apartment building in a hot and humid climate of Hong Kong.

Porritt et al. [131] compare the effects of a range of passive interventions for adapting the case study of a Victorian, late 19th century, terraced house in the south east of England in order to reduce the summertime overheating. The passive interventions include: adding one of three insulation options (loft, internal wall, external wall insulation), adding one of four solar gain control options (internal blinds, external shutters, fixed shading, low-e double glazing), painting external walls and roof in light colours to improve reflection of solar radiation, and natural ventilation strategies. The interventions, as well as a number of their combinations, are simulated using IES-VE software package [100] for summer months (June to September). It is concluded that, for a predicted test reference weather year in the 2080s, the overheating problem could be addressed purely by passive means, and the most effective interventions are wall insulation, external window shutters and painting walls in light colour. Note, however, that the study assumed the house to be occupied during evenings and mornings only, and did not consider the reduction of peak daytime temperatures.

Florides et al. [132] examine the measures reducing annual cooling load in the hot environment for a case study of a building located in Nicosia, Cyprus. The parametric study was performed with TRNSYS [25] and the design variables include roof insulation, ventilation rate, glazing type, overhang shading depth, building orientation, aspect ratio and thermal mass. The lifecycle cost analysis of the optimal measures reveals that roof insulation and efficient window glazing are most cost effective measures.

Griego et al. [133] maximize potential lifecycle energy savings for a typical residential house located in Salamanca Guanajato, Mexico, by using BEOpt+ [27]. The design variables are the walls and roof insulation levels, colour of the asphalt roof shingles, window type (single or double pane), presence of eaves and infiltration rate. Four separate optimizations are performed, for the cases of retrofit or new construction and for unconditioned or conditioned house. While the results indicate that emphasis should be put on implementing the minimum thermal insulation levels, they also show that the existing design guidelines for temperate climate zones may actually increase energy consumption.

Ruiz and Romero [134] analyze the impact of simple passive strategies on lifecycle energy use and CO_2 emissions on a case study of a two-storey house located in Cantabria, Spain. The energy simulations are performed with EnergyPlus [31], while the considered strategies include modifying building orientation, increasing southern windows-to-wall ratio, increasing wall insulation thickness as passive heating strategies, and adding overhangs, using light facade colours, adding trees in front of the eastern facade and increasing northern windows-to-wall ratio as passive cooling strategies.

Wang et al. [135] couple the structured genetic algorithm with the ASHRAE toolkit for building load calculations as the simulation engine in order to optimize the building envelope with respect to the lifecycle cost and the lifecycle environmental impact as the conflicting objective functions. The paper describes the details of calculating the lifecycle environmental impact as the cumulative

energy consumption, extended to include the abatement energy needed to remove or isolate from the environment the emissions of three major greenhouse gases (CO_2, CH_4, N_2O) and two major acidic gases (SO_x and NO_x). The design variables are the building orientation, aspect ratio, walls and roof structure, insulation levels, window type and windows-to-wall ratio for each facade. Multiple Pareto solutions are found for a case study of a single-story office building in Montréal, Canada, for which only the heating and cooling energy consumption is taken into account. It is observed that for all Pareto solutions orientation converges to zero and the windows-to-wall ratios converge to the lower bound, while the aspect ratio converges to two different values: a rectangle with longer side facing south for the minimization of lifecycle costs and nearly a square for the minimization of the lifecycle environmental impact.

Jaber and Ajib [136] perform a parametric study for a typical Jordanian residential building located in the Amman region in order to minimize its lifecycle cost. TRNSYS [25] is used as the simulation engine, while the design variables are the windows size on each facade, the presence of shading on the southern facade and the thermal insulation thickness on ceiling and walls. The results indicate that the specific energy consumption can be reduced by 25.31%, while at the same time, the lifecycle cost can be reduced by 11.67%.

Ihm and Krarti [137] use the sequential search technique coupled with DOE-2 simulation engine [22] in case study of a prototypical single-family house located in selected Tunisian cities (Tunis, Mednine, Gafsa and Nefta) in order to minimize lifecycle costs and maximize energy savings. The design variables are: building orientation, thickness of external wall and roof insulation, windows-to-wall ratio, glazing type, air infiltration level, as well as the efficiency of lighting, appliances, heating and cooling systems. The results indicate that optimal designs can cost-effectively reduce annual energy use by 50% compared to the current design practices in Tunisia, mostly by adding roof insulation, reducing air infiltration and installing more energy efficient lighting, appliances, heating and cooling systems.

Bambrook et al. [138] couple GenOpt [34] with IDA ICE [82] in order to optimize passive design of a detached, single-story house in Sydney with respect to the lifecycle heating and cooling energy cost. The design variables are the wall and roof insulation thicknesses, the window type, the shading depth, the internal thermal mass wall thickness and the night ventilation rate. Details of distinct Pareto solutions are discussed, and it is observed that the optimal solution can cost-effectively reduce the space heating and cooling energy requirement by up to 94%, compared to the current design practice in Sydney.

Hasan et al. [139] minimize the lifecycle costs for a case study of a typical Finnish, single family, detached house located in Jyväskylä, in the middle of Finland, by coupling GenOpt [34] with IDA ICE [82]. The design variables are the insulation thicknesses of the external wall, roof and floor, windows U-value and the heat recovery unit type. Further, the validation of GenOpt results, made by comparison with the brute force search results, indicates that GenOpt has either found or has come very close to the global minimum.

Verbeeck and Hens [140] search for the economically optimal balance of the energy-saving measures for retrofitting five reference buildings in Brussels, Belgium. The design variables include the insulation thicknesses of walls, roof and floor and glazing type, as well as investments in the space heating system, hot water production, solar collectors and photovoltaic panels. Using the calculation procedure from the Flemish Energy Performance Regulation, based on EN 832, the study shows that roof insulation is the most effective measure, both energy-wise and economically, followed by better performing glazing. It also shows that it is better to invest in insulation first, then in more energy efficient heating system, while renewable energy systems are least profitable investment in this study.

Tavares and Martins [141] describe the benefits obtained by employing the parametric study of comfort and energy performance in the early design stage on a case study of designing a public building located in the central region of Portugal. The parametric study is performed in VisualDOE [142], and the design variables include wall types, roofing, glazing and window frames, external shading devices, infiltration rates, mechanical ventilation rate, equipment power density, HVAC systems, thermostat settings and tolerance range. Starting from an initial design and optimizing one of the design variables at each step, they arrive at a tentatively optimal solution that offers considerable improvement in energy efficiency—reducing the heating load by 78% and the cooling load by 46%.

Roetzel and Tsangrassoulis [143] study the impact of the predicted climate change after 20, 40 and 70 years through a parametric study of a cellular office room in a building located in Athens, subjected to two occupant behaviour types (ideal and worst) and three building design types: prestige, architecturally fashionable with a fully low-e glazed facade and internal shading; low cost, based on a solid facade with a standard glazing and internal shading; and green, featuring external shading, overhang, low-e glazing and added thermal mass. The authors discuss the aspects of the thermal comfort, when building is naturally ventilated, and the energy performance for mixed mode operation. The findings indicate that, in the context of climate change, building design is the key to thermal comfort optimisation, whereas the major mitigation potential for greenhouse gas emissions is related to the occupant behaviour.

Ochoa and Capeluto [144] compare the effects of passive design strategies and active features on the energy performance and visual comfort of an office unit located in hot climate of Haifa, Israel through three parametric studies, performed with EnergyPlus, where the first study uses active features only, the second uses passive design strategies only and the third uses combination of both. The design variables in all three parametric studies are glazing type, blinds control, lighting control, night ventilation and lightshelf type. The results show that complementing passive design strategies with active features yields largest energy savings, but also that using active features only cannot replace the benefits provided by passive design strategies.

5. Conclusions

The paper reviews studies of the optimization of passive solar design strategies in buildings. It is evident that building energy simulations have to be coupled with optimization methods in order to reach high energy performance levels, especially in the conceptual design phase when the decisions made have the largest influence on building energy use.

A number of different optimization methods is used in these studies, with genetic algorithms being most widely used. However, while a number of building energy simulation programs are already established, their joint use with optimization methods is only slowly becoming part of the everyday research and design practice. One of the reasons for this is that there are no easy-to-use environments available that integrate detailed building energy simulation with genetic algorithms or other optimization methods, so that further work in this direction is needed.

Due to the fact that the building design search space becomes prohibitively large with an increase in the number of design parameters, many researchers focus the optimization studies on particular passive solar design strategies with fewer design

parameters, such as the building form, the opaque envelope components or the properties of glazing and its shading.

The studies that aim to optimize whole building's passive solar design do it so mostly through the parametric studies, which compensate for the larger number of design parameters by the smaller number of feasible values for each parameter.

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